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Discovery limits for a new contact interaction at future hadronic colliders with polarized beams

P. Taxil and J.M. Virey

Centre de Physique Théorique, C.N.R.S. - Luminy, Case 907
F-13288 Marseille Cedex 9, France

and

Université de Provence, Marseille, France

Abstract

The production of high-transverse energy jets in hadron-hadron collisions is sensitive to the presence of new contact interactions between quarks. If proton polarization were available, the measurement of some parity violating spin asymmetries in one-jet production at large transverse energy would complement the usual search for deviations from the expected QCD cross section. In the same time, a unique information on the chirality structure of the new interaction could be obtained. In this context, we compare the potentialities of various pp and $p\bar{p}$ colliders that are planned or have been proposed, with the additional requirement of beam polarization.

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email : Taxil@cpt.univ-mrs.fr ; Virey@cpt.univ-mrs.fr

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As is well known, the presence of a quark substructure can appear in hadronic collisions as an enhancement of the one-jet inclusive cross section at high transverse energy E_T . Following Eichten et al. [1] this effect is conventionally parametrized in terms of a color singlet and isoscalar contact term under the form :

$$\mathcal{L}_{qqqq} = \epsilon \frac{g^2}{8\Lambda^2} \bar{\Psi} \gamma_\mu (1 - \eta \gamma_5) \Psi \cdot \bar{\Psi} \gamma^\mu (1 - \eta \gamma_5) \Psi \quad (1)$$

where Ψ is a quark doublet, ϵ is a sign and η can take the values ± 1 or 0 . g is a new strong coupling constant usually normalized to $g^2 = 4\pi$ and Λ is the compositeness scale. We assume here that only quarks are composite, gauge bosons remaining elementary, and also that Λ is much greater than the accessible subprocess energy.

Such an enhancement has been intensively searched for, in particular at $p\bar{p}$ colliders [2]. Recently, the CDF collaboration at the Fermilab Tevatron has reported an excess of jets at large E_T with respect to the QCD prediction [3]. This would correspond to a compositeness scale $\Lambda \approx 1.6$ TeV. Although these anomalies have to be confirmed, they have triggered various speculations about the possible presence of new physics effects which could be within the reach of forthcoming experiments [4].

This paper is motivated by the following arguments.

As long as $\eta \neq 0$ the effective interaction eq.(1) violates parity and this peculiarity should be exploited, in particular because parity violating effects are strictly absent in QCD. We have found recently [5] that, provided high-intensity polarized proton beams \vec{p} were available, the measurement of some parity violating (PV) spin asymmetries in one-jet inclusive production could contribute significantly to the search for compositeness. Our study was performed in the context of the Brookhaven Relativistic Heavy Ion Collider (RHIC) : this machine will be used within a few years by the RHIC Spin Collaboration (RSC) as a polarized pp collider [6, 7], at a center of mass energy $\sqrt{s} = 500$ GeV and with a high luminosity $\mathcal{L} = 2.10^{32} \text{ cm}^{-2} \cdot \text{s}^{-1}$. With these figures and a degree of beam polarization $\mathcal{P} = 0.7$ for each beam, spin asymmetries as small as 1% should be measurable in a few months of running.

The technical progresses in the acceleration and storage of polarized proton beams have been impressive. They should make the same kind of measurements feasible at machines with higher energy, at a cost remaining a small fraction of the cost of the collider itself [8]. Various aspects of spin physics at such facilities have been already explored in details (see [8, 9, 10] and references therein).

Our goal is to compare the discovery potential and the “analyzing power“ of some future hadronic colliders with at least one polarized proton beam. We will consider the RHIC collider ($\sqrt{s} = 0.5$ TeV), the $p\bar{p}$ Tevatron ($\sqrt{s} = 2$ TeV), the upgraded Tevatron ($\sqrt{s} = 4$ TeV) in the pp or $p\bar{p}$ mode, and the CERN LHC ($\sqrt{s} = 14$ TeV), with various possibilities for the integrated luminosity in each case. Then, we will focus on the maximum value of the quark compositeness scale Λ which can be probed when parity is maximally violated ($\eta = \pm 1$) in the effective contact interaction eq.(1).

For an inclusive process like $H_a H_b \rightarrow c + X$, where c is either a jet or a well-defined particle, one can define a single-helicity PV asymmetry A_L (sometimes called the

“left-right“ asymmetry) if only one initial hadron, say hadron H_a , is polarized :

$$A_L = \frac{d\sigma_{a(-)b} - d\sigma_{a(+)b}}{d\sigma_{a(-)b} + d\sigma_{a(+)b}} \quad (2)$$

where the signs \pm refer to the helicities of the colliding hadrons. This quantity A_L is the only relevant one in case of $\vec{p}\vec{p}$ collisions since there is no known way to get intense and highly energetic polarized antiproton beams. When both proton beams can be polarized (this is the case at RHIC), one defines a double helicity PV asymmetry :

$$A_{LL}^{PV} = \frac{d\sigma_{a(-)b(-)} - d\sigma_{a(+)b(+)}}{d\sigma_{a(-)b(-)} + d\sigma_{a(+)b(+)}} \quad (3)$$

From now, $d\sigma_{a(h_a)b(h_b)}$ will mean the cross section in a given helicity configuration (h_a, h_b) , for the production of a single jet at a given transverse energy E_T and pseudorapidity η :

$$d\sigma_{a(h_a)b(h_b)} \equiv \frac{d^2\sigma^{(h_a)(h_b)}}{dE_T d\eta} \quad (4)$$

In the following, we choose to integrate $d\sigma$ over a pseudorapidity interval $\Delta\eta = 1$ centered at $\eta = 0$, and over an E_T bin which corresponds to a jet energy resolution of 10% [2].

Any helicity dependent hadronic cross section is obtained by convoluting appropriately the subprocess cross sections $d\hat{\sigma}_{ij}^{\lambda_1, \lambda_2}/d\hat{t}$, which depend upon the parton helicities λ_1 and λ_2 , with the polarized quark and/or antiquark distributions evaluated at some scale Q^2 : $q_{i\pm}(x, Q^2)$ and $\bar{q}_{i\pm}(x, Q^2)$ (explicit formulas can be found in [9, 10, 11]). Here, $q_{i\pm}$ means the distribution of the polarized quark of flavor i having its helicity parallel (+) or antiparallel (-) to the parent hadron helicity. The chosen Q^2 value is $Q^2 = E_T^2$, we have checked that changing this choice has no visible influence on our results. In the following \hat{s} , \hat{t} and \hat{u} denote the usual Mandelstam variables for the subprocess $i_a j_b \rightarrow k + l$ and are given, at zero rapidity, by :

$$\hat{s} = x_a x_b s, \quad \hat{t} = -x_a x_T s/2, \quad \hat{u} = -x_b x_T s/2 \quad (5)$$

with $x_T \equiv 2E_T/\sqrt{s}$.

Concerning the subprocess cross sections we follow the notations of [11] where :

$$\frac{d\hat{\sigma}_{ij}^{\lambda_1, \lambda_2}}{d\hat{t}} = \frac{\pi}{\hat{s}^2} \sum_{\alpha, \beta} T_{\alpha, \beta}^{\lambda_1, \lambda_2}(i, j) \quad (6)$$

$T_{\alpha, \beta}^{\lambda_1, \lambda_2}(i, j)$ denoting the matrix element squared with α boson and β boson exchanges, or with one exchange process replaced by a contact interaction. These terms will be evaluated at leading order. Note that one-loop QCD corrections for inclusive jet production in composite models have been recently estimated [12]. QCD being helicity conserving in the limit of massless quarks, one does not expect a significant influence of such corrections on the spin asymmetries.

QCD being also parity conserving, only the direct Contact term $T_{CT,CT}$, the one-gluon exchange-Contact interference term $T_{g,CT}$ and the terms involving Electroweak (EW) gauge bosons exchanges are involved in the calculations of the numerators of A_L and A_{LL}^{PV} . Of course, when evaluating the denominators in eqs.(2), and (3) -that is the unpolarized cross section which is QCD dominated- all the terms, involving quarks, antiquarks and also gluons, have to be included.

The terms involving Contact amplitudes have the following expressions [10] :

- For identical quarks $q_i q_i \rightarrow q_i q_i$:

$$T_{CT,CT}^{\lambda_1, \lambda_2}(i, i) = \frac{8}{3} \frac{\hat{s}^2}{\Lambda^4} (1 - \eta \lambda_1)(1 - \eta \lambda_2) \quad (7)$$

the crossed process $q_i \bar{q}_i \rightarrow q_i \bar{q}_i$ is obtained by changing $\hat{s} \rightarrow \hat{u}$ and $\lambda_2 \rightarrow -\lambda_2$. In case of scattering of identical antiquarks, change λ_1, λ_2 into $-\lambda_1, -\lambda_2$ in eq.(7).

- For quarks of different flavors $q_i q_j \rightarrow q_i q_j$ ($i \neq j$) : $T_{CT,CT}^{\lambda_1, \lambda_2}(i, j) = (3/8) T_{CT,CT}^{\lambda_1, \lambda_2}(i, i)$, with the same changes as above for the crossed processes $q_i \bar{q}_j \rightarrow q_i \bar{q}_j$ as well as for $q_i \bar{q}_i \rightarrow q_j \bar{q}_j$. For antiquarks $\bar{q}_i \bar{q}_j \rightarrow \bar{q}_i \bar{q}_j$, change λ_1, λ_2 into $-\lambda_1, -\lambda_2$ in the first expression.

Due to color conservation rules, the interference between the one-gluon exchange amplitude and the Contact term amplitude occurs only for identical quarks (identical antiquarks), therefore for $q_i q_i \rightarrow q_i q_i$:

$$T_{g,CT}^{\lambda_1, \lambda_2}(i, i) = \frac{8}{9} \alpha_s(Q^2) \frac{\epsilon}{\Lambda^2} (1 - \eta \lambda_1)(1 - \eta \lambda_2) \left(\frac{\hat{s}^2}{\hat{t}} + \frac{\hat{s}^2}{\hat{u}} \right) \quad (8)$$

with the change λ_1, λ_2 into $-\lambda_1, -\lambda_2$ for $\bar{q}_i \bar{q}_i \rightarrow \bar{q}_i \bar{q}_i$ or $\hat{s} \rightarrow \hat{u}$ and $\lambda_2 \rightarrow -\lambda_2$ for $q_i \bar{q}_i \rightarrow q_i \bar{q}_i$. Note that \hat{t} and \hat{u} being negative, $\epsilon = -1$ (+1) corresponds to constructive (destructive) interference [1].

We have checked that the influence of the interference between EW and CT amplitudes is quite weak (the expressions for the dominant terms can be found in [5]). We will call generically ASM the PV asymmetry (A_L or A_{LL}^{PV}) which is expected in the Standard Model as due to EW boson exchanges and also to QCD-EW interference. These standard PV asymmetries have been studied for a long time [13, 14] and the correct expressions for the helicity dependent amplitudes can be found in [11]. In any case, ASM remains small although it increases in magnitude with E_T at a fixed \sqrt{s} value [15]. This is due to the increasing importance of quark-quark scattering relatively to other terms involving gluons. The non-standard asymmetries exhibit the same behavior. For illustration we give in Table 1 the values obtained for ASM in various collider configurations for a value of $x_T \approx 1/3$, which is relevant for our study. In this table, ASM is given in the first column with a “theoretical“ error which corresponds to our estimate of the present uncertainties due to the imperfect knowledge of the polarized quark and antiquark distributions. For this purpose we have used some recent sets of distributions (GS95 [16], GS96 [17], GRV [18] and BS [19]) which fit all the available data from polarized deep-inelastic experiments. Note that, since real gluons are not involved in the process we consider, our estimates are not

plagued by the uncertainties associated to the imperfect knowledge of the polarized gluon distributions $\Delta G(x, Q^2)$. On the other hand, the statistical error ΔA for an integrated luminosity L_I is given by (for A_{LL}^{PV}) :

$$\Delta A \simeq \frac{1}{\mathcal{P}} \sqrt{\frac{L_1}{L_I}} \frac{1}{\sqrt{N_{evts}^{++} + N_{evts}^{--}}} \quad (9)$$

where the number of events $N_{evts}^{++(--)}$ corresponds to $L_1/4$. When the measurement of A_L is concerned one has : $\Delta A(A_L) \simeq \frac{1}{\sqrt{2}} \Delta A(A_{LL}^{PV})$. In general, A_{LL}^{PV} is larger than A_L in the same kinematical conditions, for a statistical error which is comparable. Therefore, it is better to retain the former when its measurement is feasible.

Of course, in a given hadronic configuration (pp or $p\bar{p}$), when \sqrt{s} increases at fixed x_T , a greater luminosity is needed to get the same number of events, and therefore the same value for ΔA .

Concerning ASM ($\equiv A_L$) in $p\bar{p}$ collisions, it is dominated by $q\bar{q}$ annihilation and its magnitude is very small. This is due, first, to the crossing symmetry : annihilation terms contribute much less than scattering terms to the numerator of A_L ; second, to the important cancellation which occurs between the QCD-EW interference terms (T_{gZ} or T_{gW}) on the one hand, and the pure EW terms which are relevant to the particular process (T_{WW} , T_{ZZ} , $T_{\gamma Z}$) on the other hand [11].

Turning now to the search for non-standard effects, we give in Fig. 1. the 95% confidence level limits on the compositeness scale Λ which could be obtained at the future colliders we consider. We compare the limits obtained from measurements of the unpolarized one-jet cross-section alone and from the measurement of the PV spin asymmetry A_L or A_{LL}^{PV} in the same channel. The strategies which have been followed are based on a χ^2 analysis, they are described below :

- *Cross sections :*

Using GRV distributions, we have compared $d\sigma(\text{QCD+EW+CT})$ to the standard QCD-dominated cross section. To calculate the χ^2 , we have added in quadrature a systematic uncertainty of 50% to the statistical uncertainty [3]. As noticed by CDF [2], this kind of

Collider	ASM (%)	ΔA (%)
RHIC (pp), $L_1 = 0.8 fb^{-1}$	1.36 ± 0.6	0.7
Tevatron ($p\bar{p}$), $L_1 = 1 fb^{-1}$	-0.33 ± 0.12	2.6
Di-Tevatron ($p\bar{p}$), $L_1 = 10 fb^{-1}$	-0.34 ± 0.13	2.0
Di-Tevatron (pp), $L_1 = 10 fb^{-1}$	3.11 ± 1.11	3.0
LHC (pp), $L_1 = 100 fb^{-1}$	4.03 ± 1.0	6.8

Table 1: Standard ASM (A_{LL}^{PV} for pp , A_L for $p\bar{p}$) for $x_T \approx 1/3$, at various colliders with integrated luminosity L_1 along with the statistical error ΔA on ASM.

analysis is dominated by the upper part of the E_T spectrum. As a check, we recover the published CDF limit, $\Lambda = 1.4$ TeV, obtained with a data sample of 4.2 pb^{-1} [2]. Using some other (unpolarized) quark distributions which are currently in use yields the same results.

- *Asymmetries* :

In this case, the strategy is different since a reasonable number of events is necessary for measuring an asymmetry. Therefore, the analysis is dominated by the region $x_T \approx 0.25 - 0.4$. On the other hand, in an asymmetry which is a ratio of cross sections, certain systematic errors such as detector efficiencies and absolute luminosities cancel [6]. We have been conservative, choosing $(\delta A/A)_{\text{sys}} = 20\%$. We have also chosen a set of polarized distributions (GRV) in which the quarks carry a small fraction of the proton spin, at a variance with e.g. the BS distributions. The magnitude of the spin asymmetries are then reduced and the bounds we give on Λ are conservative. It has also to be kept in mind that our knowledge about the polarized partonic distributions will improve drastically in the future, thanks to the HERMES experiment at HERA [20] and, especially, thanks to the RSC program itself (see e.g. [7, 11]).

One can see from Fig.1 that measuring the PV spin asymmetry gives in general much better discovery limits for the compositeness scale than the measurement of the unpolarized cross section. This behaviour is independent of the left-handed or right-handed nature of the new interaction, as long as PV is maximal. The key factor turns out to be the integrated luminosity : at a fixed c.m. energy, the spin asymmetry gives a better sensitivity as soon as the large luminosity allows to get a big number of events with $x_T \geq 0.3$. The situation at RHIC is a particular case since the low value of \sqrt{s} yields some bounds which are below the present CDF limit (from the measurement of σ). Note that the bounds we obtain from A_{LL}^{PV} are larger by ≈ 1.3 TeV than the ones we had obtained in a simpler analysis [5].

In each case, we have made the distinction between constructive and destructive interference between QCD and CT amplitudes. As already noticed in EHLQ [1], the non-standard effect is more visible when $\epsilon = -1$. This is true from the cross section and also from the PV spin asymmetry. However, the respective weights of the direct $T_{CT,CT}$ term and the $T_{g,CT}$ interference term vary in function of the collider (pp or $p\bar{p}$) configuration. As a consequence, in the pp mode, the bounds on Λ are more influenced by the sign of ϵ when they come from the cross section measurement than from the asymmetry. The situation is reversed in the $p\bar{p}$ mode. In any case, at a given luminosity, the Di-Tevatron is preferred in the pp mode.

Finally, it is important to note that, if an effect is observed in jet production, the polarized collider will not only be a tool for discovery but also for analysis since it will provide valuable information on the chirality structure of the new interaction. More precisely, from the way A_L or A_{LL}^{PV} deviates from the ASM value, it is easy to get the sign of the product $\epsilon\eta$, even for the largest value of Λ in a given collider configuration. For instance, at RHIC for $x_T = 1/3$ with the GRV distributions, the Standard Model expectation is $A_{LL}^{PV}(\text{SM}) = 1.3 \%$ (with an error of 0.8% with $L_1 = 0.8 \text{ fb}^{-1}$). Adding the contact interaction with a scale $\Lambda = 1.6$ TeV, we obtain $A_{LL}^{PV}(\epsilon\eta = 1) = -1.2 \%$ and

$$A_{LL}^{PV}(\epsilon\eta = -1) = 3.9 \text{ \%}.$$

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Figure captions

Fig. 1 95% C.L. discovery limits for the compositeness scale Λ at future hadronic colliders with polarization, in case of constructive ($\epsilon = -1$) or destructive ($\epsilon = +1$) interference between the QCD and the non-standard amplitudes. The χ^2 analysis is based on the unpolarized one-jet cross section or independently on the PV spin asymmetry A_{LL}^{PV} (A_L in case of $p\bar{p}$ collisions). These limits are independent of the sign of the parameter η ($\eta = \pm 1$).

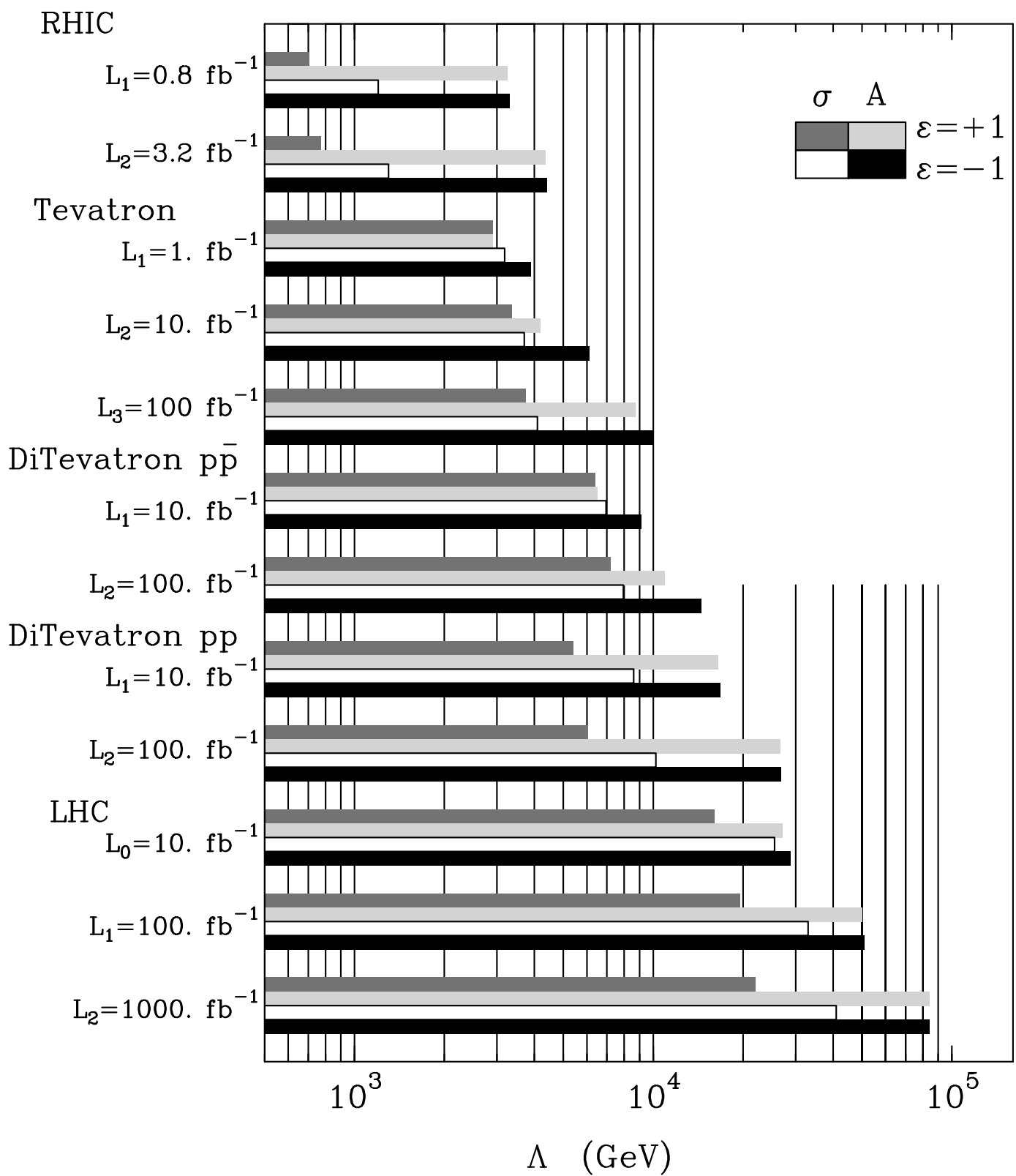


Fig 1